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High Impact Papers in Power Engineering, 1900 – 1999

G. T. Heydt
heydt@asu.edu
Arizona State University
Tempe, AZ, USA

S. S. Venkata
venkata@iastate.edu

Nagaraj Balijepalli
nagaraj@iastate.edu

Iowa State University
Ames, IA, USA

Celebration 2000

The passing of the year 1999 into history, and the recognition of the roll-over of the calendar to 2000 has not occurred without reminiscence of the past and wonderment for the future. The use of digital controls, accounting, and computer operations in many elements of modern life has produced the scare popularly known as 'the Y2K bug'. In power engineering, some citizens worried about the power system and its component power generating stations to withstand the rollover. But we have come though the calendar change totally unscathed, and it is time to celebrate the past as well as work for the future. Part of the celebration is, it seems, to take the time to recognize the accomplishments of the past century. Power engineering has a considerable number of accomplishments that should be acknowledged at this time.

In 2000, that National Academy of Engineering of the United States invited participating professional engineering societies (ASME, IEEE, AICHE, ANS, ASCE, AIAA) to submit a list of nominations for the engineering feats of the past century that have had the greatest impact on society. Among approximately 100 nominations, including the formation of the Internet, the invention of the airplane, and the development of the transistor, one nomination was selected as *the* most important feat of the century: this was the mass electrification of the world and the utilization of electric power to relieve man of his burden.

As part of the year 2000 celebration, the organizers of the North American Power Symposium 2000, held in Waterloo, Ontario, chose to recognize accomplishments of the past by assessing the written contributions to electric power engineering. A list of 39 technical papers was collected by the authors of this paper. These nominations were collected by an announcement in the power engineering listserver known as the Power Globe, by an announcement at the 1999 Summer Power meeting in Edmonton, Alberta, and by an announcement at the 2000 Winter Power Meeting in Singapore. Additionally, the organizers informally polled their colleagues and students. Over 50 nominations were received as high impact papers of the years 1900 - 1999. Approximately 11 of the informal nominations were unable to be identified in the literature, and thus the list was reduced to 39 nominations.

The high impact paper list

The 39 high impact papers are deemed to be an unscientific and possibly faulty list of papers. This is concluded from email interchanges from researchers around the world who lamented that some papers had been omitted (especially papers by A. Blondel -- but the main papers of Blondel were published in 1895-99, outside the time window of interest). In some cases, papers written in languages other than English were not nominated – not because they were not of high impact, but because our colleagues were not conversant with the work. A further confusion occurred when some nominations were entire books. With all these difficulties, the high impact paper list was nonetheless compiled.

The 39 nominated high impact papers appear in Table (1).

The final four

The indicated 39 papers and books were circulated to colleagues, members of the Power Globe, and some students. These persons were asked to indicate the three papers that seemed to be the highest impact papers. The results of the vote are:

- Over 231 'votes' were cast
- About 73 persons responded to the call for votes
- Respondents came mostly from the United States (approximately 50.6 %), but many other countries and regions were well represented as shown in Figure (1). Of the seven continents of the world, five continents were represented in the vote.
- About 20% of the respondents seemed to be from industry. The remainder seemed to be university professors but some students also voted.

Table (1) Nominated high impact papers of 1900 – 1999

Year	*Authors*	*Title*	*Citation*
1908	W. Lyon	*Problems in Electrical Engineering Alternating Currents*	McGraw Hill, NY
1918	C. Fortescue	Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks	Trans. AIEE, v. 37, p. 1027-1140
1925	C. Fortescue	Transmission Stability, Analytical Discussion of Some Factors Entering Into The Problem	Trans. AIEE, September, p. 984 - 994
1926	J. Carson	Wave Propagation in Overhead Wires with Ground Return	Bell System Technical Journal, October, v. 5, p. 539-554
1929	R. Park	Two Reaction Theory of Synchronous Machines	Trans. AIEE, v. 48, p. 716-730
1929	C. Fortescue, A. Atherton, J. Cox	Theoretical and Field Investigations of Lightning	Trans. AIEE, v. 48, April, p. 449-468
1931	E. Clarke	Simultaneous Faults on Three Phase Systems	Trans. AIEE, v. 50, March, p. 919-941
1933	C. Wagner, R. D. Evans	*Symmetrical Components*	McGraw-Hill, NY
1933	L. Bewley	*Traveling Waves on Transmission Systems*	John Wiley, NY
1937	C. Concordia	Two Reaction Theory of Synchronous Machines with Any Balanced Terminal Impedance	Trans. AIEE, v. 56, p. 1124-1127
1937	C. Concordia, J. Butler	Analysis of Series Capacitor Applications Problems	Trans. AIEE, v. 56, p. 975-988
1938	E. Clarke	Problems Solved by Modified Symmetrical Components	General Electric Review, v. 41, p. 488-494, 545-549
1942	Westinghouse Electric	*Electrical Transmission and Distribution Reference Book*	Westinghouse, E. Pittsburgh, PA
1943	E. Clarke	*Circuit Analysis of AC Power Systems, Symmetrical and Related Components*	John Wiley, NY
1944	C. Concordia	Steady State Stability of Synchronous Machines as Affected by Voltage Regulator Characteristics	Trans. AIEE, v. 63, p. 215-220
1951	C. Condordia	*Synchronous Machines*	Chapman and Hall, London
1952	A. Fitzgerald, C. Kingsley	*Electric Machinery*	McGraw Hill, NY
1956	C. Mason	*The Art and Science of Protective Relaying*	John Wiley, NY
1956	J. Ward, H. Hale	Digital Computer Solution of Power Flow Problems	Trans. AIEE, v. 75, Pt. III, p. 398-404
1959	J. Van Ness	Iteration Methods for Digital Load Flow Studies	Trans. AIEE, v. 78, August, p. 583-588
1959	L. Kirchmayer	*Economic Control of Interconnected Systems*	John Wiley, NY
1960	W. Tinney, C. McIntyre	A Digital Method for Obtaining a Loop Connection Matrix	Trans. AIEE, v. 79, October, p. 740-745
1961	N. Cohn	*Control of Generation and Power Flow on Interconnected Power Systems*	John Wiley, NY
1962	J. Carpentier	Contribution a' L'Etude du Dispatching Economique	Bulletin Societe Française des Electriciens, Ser. 8, v. 3, August, p. 431-447
1963	J. Carpentier, J. Siroux	L'optimisation de la Production a' l'Electricite de France	Bulletin de la Societe Française des Electriciens, March

1963	H. Brown, G. Carter, H. Happ, C. Person	Power Flow Solution by the Impedance Matrix Method	Trans. AIEE, v. 82, pt. III, p. 1-8
1963	G. Kron	*Diakoptics*	Macdonald, London
1966	A. El-Abiad, K. Nagappan	Transient Stability Regions of Multimachine Power Systems	IEEE Trans. Power Apparatus and Systems, PAS-85, No. 2, p. 169-179
1968	G. Stagg, A. El-Abiad	*Computer Methods in Power Systems Analysis*	McGraw Hill, NY
1968	H. Dommel, W. Tinney	Optimal Power-Flow Solutions	IEEE Trans. Power Apparatus and Systems, PAS-87, p. 1866-1876
1970	R. Billinton	*Power System Reliability Evaluation*	Gordon Breach Science Publishers
1972	N. Hingorani	Report on DC Transmission	IEEE Trans. Power Apparatus and Systems, PAS-91, No 6, p. 2313-2318
1973	P. Anderson	*Analysis of Faulted Power Systems,*	Iowa State University Press
1974	B. Stott, O. Alsac	Fast Decoupled Load Flow	IEEE Trans. Power Apparatus and Systems, PAS-91, No. 3, p. 859-869
1977	P. Anderson, A. Fouad	*Power System Control and Stability*	Iowa State University Press
1978	F. Alvarado	Penalty factors from Newton's method	IEEE Trans. Power Apparatus and Systems, PAS-97, No 6, p. 2031-2040
1978	G. Rockefeller	Fault Protection with a Digital Computer	IEEE Trans. Power Apparatus and Systems, PAS-88, No. 2, p. 438-464
1981	E. Abed, P. Varaiya	Oscillations in Power Systems via Hopf Bifurcations	Proceedings 20th Conference on Decision and Control, San Diego, IEEE Press
1995	C. Concordia, J. Paserba	Opportunities for Damping Oscillations by Applying Power Electronics in Electric Power Systems	CIGRE Symposium, Tokyo, report No. 38.01.07

- The 'vote' taken should not be viewed too scientifically: that is, the vote was contaminated by the fact that books were mixed into the list, many excellent papers were missing (especially papers written in German, French, Russian, and other languages). Also, a few voters voted for four papers, and a few voted for only one. The deadline for the receipt of votes was not given and votes may still be trailing in at this time! However, it seems to be a consensus that Charles Fortescue's paper on symmetrical components is highly regarded in the power engineering community.

The 'top eight' papers are shown in Table (2).

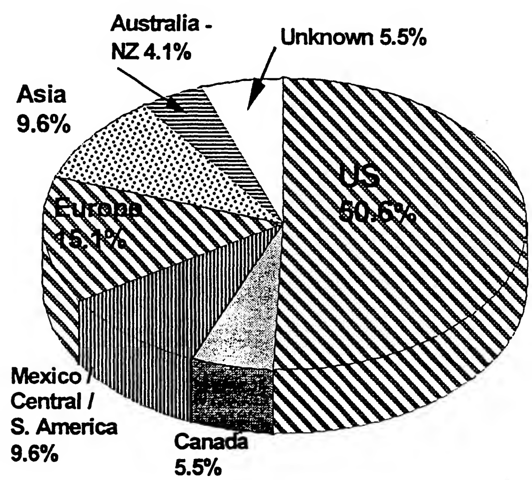

Figure (1) Respondent origins

Table (2) Eight high impact papers of the past century

Votes received from 73 respondents	*Author*	*Year of publication*
47	Fortescue	1918
36	Park	1929
19	Ward, Hale	1956
19	Carson	1926
17	Dommel, Tinney	1968
11	Stott, Alsac	1974
9	Bewley	1933
7	Concordia	1944

The selection of the final four papers to be presented at NAPS 2000 in Waterloo was made by the authors of this paper in collaboration with the conference organizers. The selection of four papers was done even more unscientifically and more inaccurately than the 'vote'. The main considerations in the selection were:

- Results of the informal vote
- Recommendations by colleagues
- Need to balance the selection over the years
- Balancing of areas of interest
- Recruitment of a suitable person to re-present the original paper
- Opinions of the organizers of this session.

The final four papers are:

1. Charles L. Fortescue, "Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks," Transactions of the AIEE, v. 37, p. 1027-1140, 1918.
2. Robert Park, "Two Reaction Theory of Synchronous Machines," Transactions of the AIEE, v. 48, p. 716-730, 1929.
3. James Ward, Harry Hale, "Digital Computer Solution of Power Flow Problems," Transactions of the AIEE, v. 75, Pt. III, p. 398-404, January 1956.
4. John R. Carson, "Wave Propagation in Overhead Wires with Ground Return," Bell System Technical Journal, v. 5, p. 539-554, October, 1926.

About the papers

Fortescue

The sinusoidal steady state analysis of three phase circuits is traced to Ferraris and Lamme in 1895. These early power engineers analyzed the rotation of magnetic fields in electric machines, and L. G. Stovkis seems to have invented the idea of resolving the fields into a positively rotating part, a negatively rotating part, and a pulsating field. In Fortescue's 1918 paper, the concept of symmetrical components not only for fields but also for voltages and currents is set out in detail. The Fortescue paper expounds the method to analyze unbalanced three phase circuits, the use of sequence operators, and the application to systems of high phase order. Fortescue proposes the term *symmetrical coordinates* for the method.

Park

This paper presents an extension to the work of Blondel, Dreyfus, Doherty, and Nickle. This paper presents seminal work on the development of Park's transformation: this transformation is widely applied in the analysis and study of both synchronous machines and asynchronous machines. The salient aspect of this work is a novel transformation that transforms linear differential equations with time varying coefficients to linear differential equations with time *invariant* coefficients. The time varying coefficients arise due to inductances that vary with time and rotor position. The transformation converts the inductances to constant values. Park's transformation can be viewed as a transformation from stator variables to the rotor reference frame.

Ward and Hale

Before the advent of computer-aided analysis of power systems, the majority of power flow problems were solved using the AC network analyzer. Setting up of the AC network analyzer for each study took considerable amount of time and effort for large-scale systems. The assessment of line losses and incremental power loss were problematic because of insufficient precision. The analyzers were dedicated instruments that represented a substantial investment and required considerable care and maintenance. In such an era, Ward and Hale published a seminal paper in which they proposed a nodal formulation of the equations representing the electrical networks, along with a computer-aided method for solving these equations. The main contributions of this paper are the automatic generation of the system admittance matrix and the iterative solution of the power flow equations that does not involve matrix inversion. Truly, the formulation of the load flow problem as $\Delta P = 0$, $\Delta Q = 0$ was also a significant contribution. A rigorous treatment of off-nominal and tap-changing transformers is also expounded in the paper. It is this remarkably unassuming paper that has firmly established the superiority of the Gauss-Seidel formulation of the power-flow solution and has exerted lasting influence on the subsequent development of the various power system planning and operations studies.

Carson

The paper by Carson sets out the formulas for the impedance of overhead transmission lines. The development is the electromagnetic analysis of overhead conductors above a conducting plane. The conductivity of the Earth is considered in detail, but is assumed to be uniform. The geometries considered are relatively simple, but more complex configurations can be found by superimposing results. The entire analysis is in complex notation, and therefore the usual assumption of sinusoidal

steady state is made. The solutions involve difficult integrals, and series formulations are proposed. The author laments the complexity of the solution, but offers the good news that the series generally converge rapidly. An application to electric railways is presented. This paper has become the basis of all formulas for the impedance of overhead transmission lines, and the formulas given are known as *Carson's formulas*.

Why the papers are important

The high impact papers represent engineering work that forms a basis of modern power engineering. The 39 papers collected, as well as many other papers, form the foundations of AC circuit theory, energy conversion, system theory, transmission and distribution, and utilization of electric power. Each of these areas is an indispensable building block to the mass electrification of the world and the utilization of electric energy for the many tasks we know today. Perhaps the paper by Fortescue is the most fundamental of the papers collected: this paper sets down the theory of symmetrical components as well as the methods to be used in the steady state analysis of AC circuits. The Fortescue paper is used daily by modern power engineers who deal with three phase circuits. At the time the paper was written in 1918, it was unclear that three phase AC technologies would be used for virtually all bulk power generation and transmission. Except for DC technologies, which have relatively recently come to some degree of fruition, three phase circuits have been the mainstay of power engineering. The analysis of these circuits in an efficient and comprehensible way is the key importance of the Fortescue paper.

The importance of the Park paper is that nearly all detailed synchronous machine modeling has utilized Park's equations. Because Park's model is a linear time invariant differential equation, the model is indispensable for transient analysis of synchronous machines. It is true that there are simpler models that are mainly applicable in steady state, balanced conditions, but the Park model has survived as the benchmark of machine models. Improvements have been made in the area of identification of parameters, the implementation and simulation of Park's equations, and in modeling nonlinearities (e.g., saturation).

The testimony that power engineers in the electric utility industry, including all the deregulated components of that industry, rely on electric power flow studies is a statement of the importance of the Ward and Hale paper. The formulation of total active and reactive power at buses in combination with the Kirchhoff laws to model how power systems accept and transport power is a key element to how modern power systems are both planned and operated. The power flow problem is a basic building block of power system analysis. Improvements have been made (mainly the application of the Newton Raphson method to its solution, and the utilization of the decoupled nature of P-Q / δ-$|V|$ -- also 'high impact papers'), but the basic formulation and models used are those of Ward and Hale.

The importance of the Carson paper is documented by the fact that most transmission line models in the power industry use Carson's formulas. The series solutions have been modified and improved for convergence, and exciting software has been developed for this purpose, but the basic concept is that of Carson.

Summary

Power engineering, like all other scientific and engineering disciplines, builds on the past work of leaders of the field. The pathfinding work of all power engineers of the past is acknowledged and the special attainments documented by 39 technical papers listed in this paper are singled out for recognition. A sampling of contemporary power engineers choose to give particular recognition to Charles Fortescue, Robert Park, James Ward, Harry Hale, and John Carson for their contributions to electric power engineering.

Acknowledgements

The authors acknowledge the 73 respondents of the Power Globe vote, and the approximately 50 individuals who nominated papers. Dr. Vijay Vittal of Iowa State University kindly provided a paragraph on Park's method of coordinate transformation for rotating machinery. Special thanks goes to Dr. A. P. S. Meliopoulos for supplying a copy of one of the selected papers, Drs. Claudio Cañizares and Vijay Vittal for valuable advice, Professor Richard G. Farmer for reading the draft manuscript, and Professors A. Meliopoulos, C. Gross, and A. Pahwa for participating in the presentation of the papers. Authors Balijepalli and Heydt note with thanks Dr. S. S. Venkata for also participating in the presentation of the papers.

Waterloo Ontario, October 1900

G. T. Heydt
Arizona State University
Tempe, AZ, USA

Canada - 1900

The date is *October 23, 1900.* The place: *Waterloo, Ontario, Canada.* The Toronto Telegraph reports that a cold wind will be bearing down on Waterloo from Georgian Bay and points north, and the overnight low will be in the 30's – not unkind for this time of year. The news of the day is full of stories on the opening of the new Paris electric metro (following London just ten years ago); Prime Minister Wilfrid Laurier appealing to the Prairie Indians for calm over disputes about Crown land boundaries; the Manitoba School question; and the increase in demand abroad for Canadian wheat. The April fire in Hull now has been deemed to have claimed the homes of 12,000 persons with seven lives lost – and damage in the amount of $15 million dollars. In the United States, the Democratic National Convention in Kansas City has nominated a solid ticket of Bryan and Stevenson – likely to be the next president and vice-president of that country.

The greatest news of the day is the gold strike in British Columbia. As miners pour into western Canada from the United States and other parts of the world, the extent of the unpopulated prairie lands is becoming known. The supply of free land in the United States is virtually exhausted, and the frontier there is closed. Settlers are venturing from as far away as Russia to establish farmsteads on the open wheatland. This immigration has resulted in pressure on the Crown to establish at least one province between Manitoba and British Columbia. A benefit resulting from the gold rush is the discovery of other minerals in the Canadian wilds. As early as seventeen years ago, nickel was found at Sudbury, Ontario and only ten years ago large deposits of base-metal ores were uncovered in southern British Columbia. Canada is quickly becoming perceived around the world as a mineral-rich nation with great untapped potential.

It seems that as of this year, Prime Minister Laurier's only serious political difficulties are stemming from his inability to satisfy fully the imperialists among his followers. Great Britain received support in the ongoing Boer War from the other self-governing colonies, and Laurier reluctantly commits Canada as well. His decision sharpens the controversy between the two nationality groups regarding Canada's proper responsibilities to Britain in the future. The solid position of Britain in South Africa is documented by seizure of the Transvaal on September 1. But Laurier continues to resist pressures to tie the bonds of empire still more tightly after the victory in South Africa. It seems that seeds of distrust concerning Laurier's policies are being sown on both sides of the wall that is rising between Canadians of French and of English descent.

In the United States, Republican President McKinley is still mourning the loss of Vice President Garret A. Hobart last November in New Jersey. Political pundits believe that the Governor of New York, Mr. Theodore Roosevelt, will be selected as the next vice-president of the country.

Engineering to alleviate man's burden and cross the miles

Interesting new results have been published by William Crookes from his investigations in a private laboratory. His studies of electrical discharges in gases, which followed the development of the cathode ray tube by Pluecker and Hittorf, and his observations of cathode rays and the dark space at the cathode led to the discovery of x-rays and of the electron. Crookes is a believer in the occult and in the 1870's claimed to have verified the authenticity of psychic phenomena. Later he became involved in the Theosophical Movement and there are references to his having exorcised demons. In 1897 Crookes was knighted by Queen Victoria who is also reputed to have an interest in the occult.

Interesting new experiments in magnetism seem to indicate that coils at great distance from a magnet may be able to detect the motion of that magnet. It is most unlikely that these phenomena will have any practical value, but experiments here in Canada are underway to use the phenomenon for distant communications.

Power Engineering takes a vital role

The advances in mining and manufacturing here in Canada, as well as in Australia, South

Africa, and the United States has given new impetus to a fast growing field: *electric power*. The Germans are clearly ahead in the development of this technology – as they are in development of coal and all manners of mechanical devices. This remark is evidenced by the German manufacture trams along Dominion Street in Waterloo. Siemens is dominating the field of motors, transformers, and electrical instruments. Although it is unlikely that electricity can power all phases of manufacturing and industry, it is likely that our utilization of horses and other beasts of burden will continue to be reduced in the next decade (witness the drastic reduction of horse drawn trams along King and Yonge Streets in Toronto – and there is hardly a blacksmith to be found today on Ellen Street in Waterloo).

There is speculation that the electric automobile will prevail in the near future: optimists conjecture that travel time between Toronto and Winnipeg will be slashed to four days, and a network of electric battery charging stations will be developed along the northern shores of the great lakes. A trip from Waterloo to St. Jacobs or New Hamburg now takes just an hour on solid earthen roads. The proponents of automobile travel point to the present possibility of travel to Montréal in less than a day. Ontario has a vital part of Canadian development: with nickel in the north, and Niagara in the south, and the steady demand for Ontario-made goods in the west, the province seems destined for considerable development.

For the past 16 years, electric power has been promoted by a group of engineers with the American Institute of Electrical Engineers (AIEE) at the helm here in Canada and the United States. The titular seat of the AIEE has finally been chosen as New York City, possibly to recognize the long-standing (20 years) Pearl Street Station of Thomas Edison. Further evidence of the importance of electric power to Canada:

- The rapid conversion of horse drawn trams to electric traction (expected to be complete in two years)
- The use of Schukert (German manufacture) electric trams, operated with 20 horsepower DC motors
- Brill (American manufacture) tram fittings imported from Philadelphia for use with the Schukert trams
- Toronto central generating stations greater than 1000 horsepower distributing 110, 220, and higher voltages
- Experimental 6000 V, three phase generating voltages
- The power level of 25,000 kW is projected as the maximum level that the city of Toronto and environs might use.

The experts of the day feel that electrical technologies will greatly impact transportation, mining, and general industrial needs. The electrification trends of the 80s and 90s show little slowing, and full city electrification by 1910 is possible. The field is strong, changing, and a considerable career attraction to young engineers.